Bagels, Bison and Bosons
(the original name of my talk!)

Jim Kerby

Welcome!

Fermilab is:

- the most powerful particle accelerator in the World.
- home to 2000 government contractor employees, and more than 1000 visiting scientists from Universities and some tens of countries.
- operated for the Department of Energy by a consortium of ~90 universities, with a yearly operating budget of ~300M$.
- 37 years old--home to 6800 acres of Illinois Prarie with a 4 mile circumference accelerator in the middle (and a couple of smaller ones on the side)

I hope to pass along some of what we do, how we do it, and why during the next couple of hours.

Questions are welcome (I just need to make my kids' soccer game in Geneva at 2:30…)

Your speaker / tour guide…

The disclaimer!

- I'm a mechanical engineer by training (BS / MS Purdue)
- I'm in my 18th year at the lab.
- I've worked on both detectors and accelerators, and some of the equipment you need to make them operate.
- I've made a reasonable attempt at fact checking for this talk, but if I've made an error, it's mine.
- I'm not much into jargon. You'll catch some 'Hoosier-isms'. (Quiz on those later…)

What you're in for…

1. A talk (here). There just needs to be some background. A few parts:
   A. What Fermilab is
   B. What we know (or think we know)
   C. How we accelerate things
   D. How we detect things
2. A walk (not here). This will include:
   A. An overview (our 15th floor)
   B. The first 2 accelerators in our chain
   C. The Main Control Room
   D. A detector (CDF)
   E. The magnet factory (my home)

You're warned!
(we'll adjust as needed)

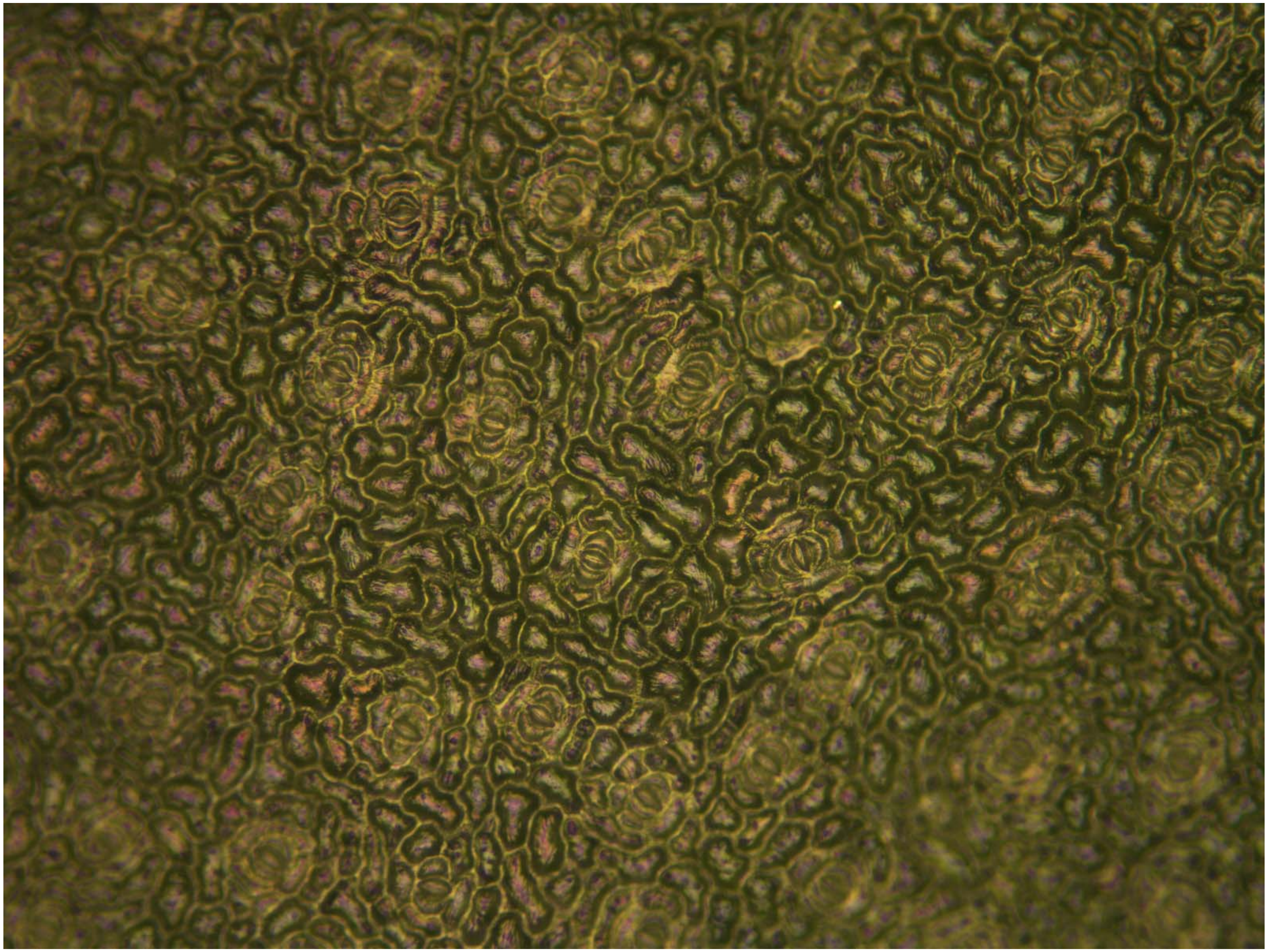
What Fermilab Is

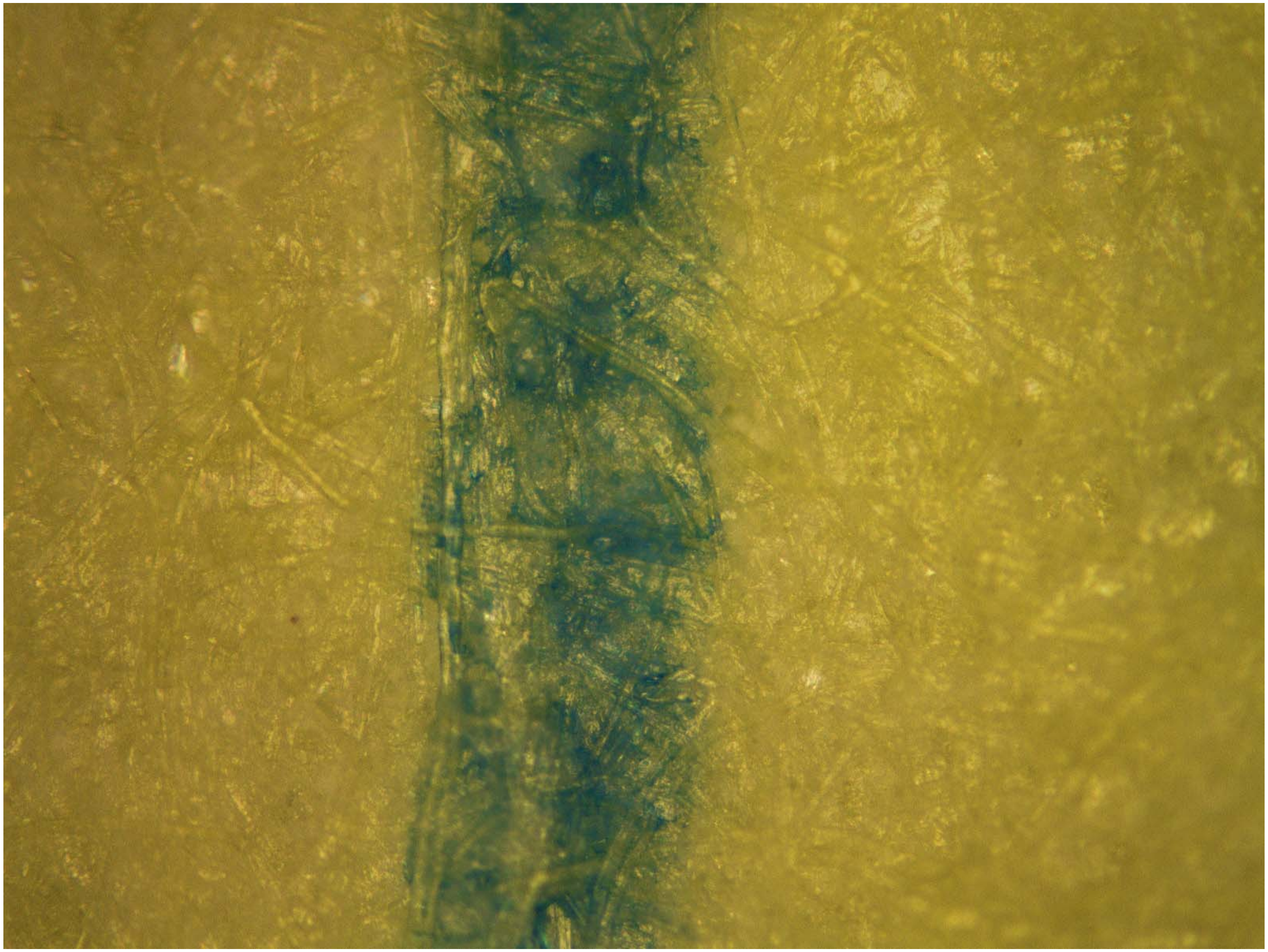
A very very very powerful microscope. It is a one of a kind tool to experimentally explore the smallest, smallest components of matter, which everything is made of.

A microscope generates information by using light, transmitted through a sample.

The transmitted light is then detected, after some optics, by your eye.

Fermilab has both the microscope and the detector (most of the time).





Optical Microscopes

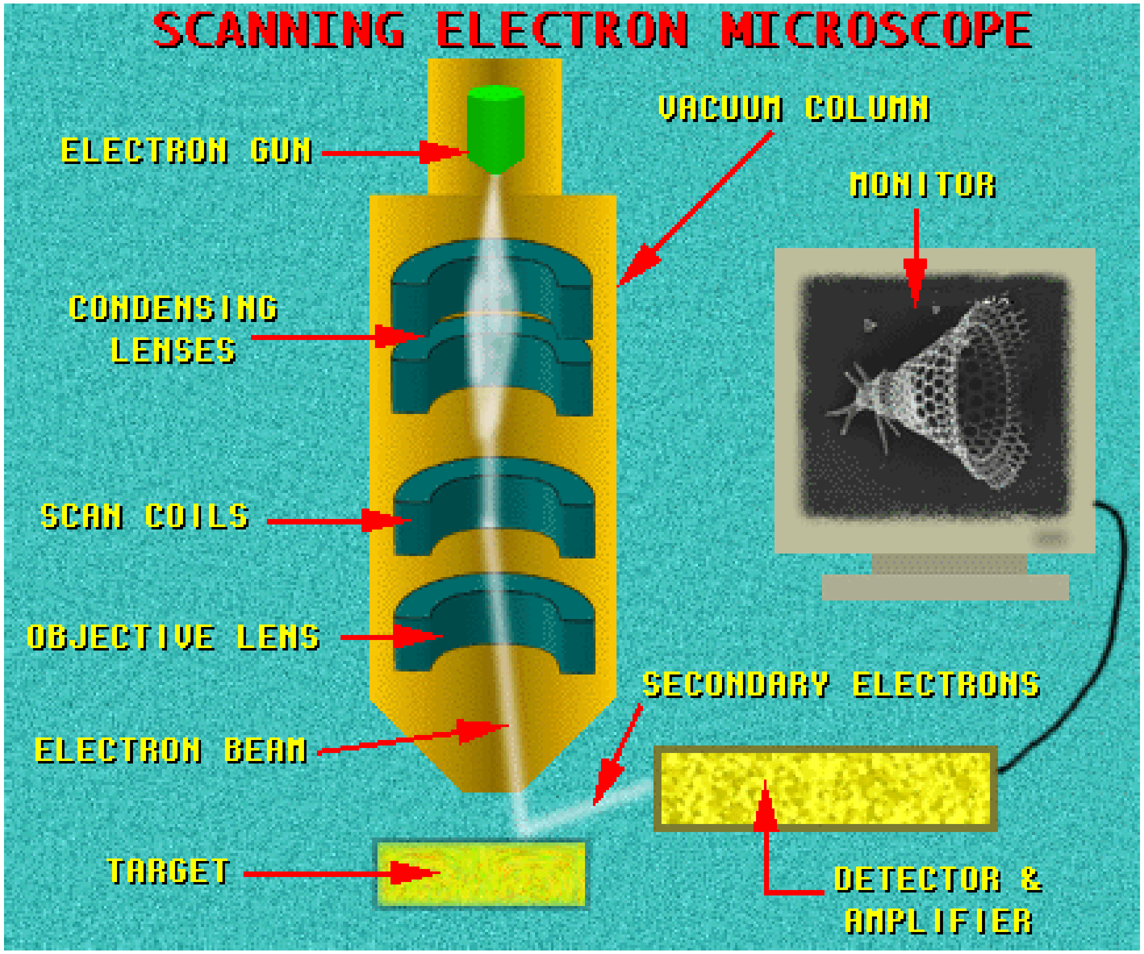
At 1000x magnification in a very special optical microscope, you can watch cell nuclei divide if you're so inclined…

This is pushing the limits for an optical system…

Cool! Why bother with anything else?

The more you see, the more you know…

- Electron microscopes use electrons instead of light. They can get in the many thousands of magnifications…

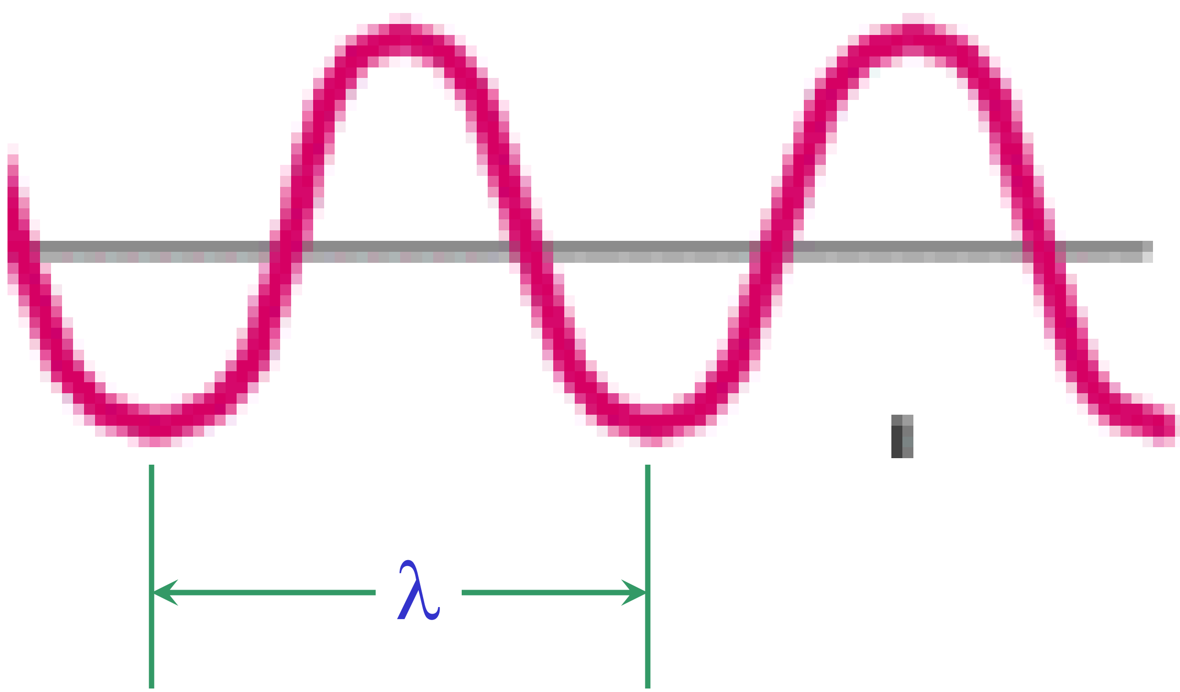


Electron microscopes have a resolution on the order of 2 Angstroms (0.0000002mm), about 1000x better than an optical microscope

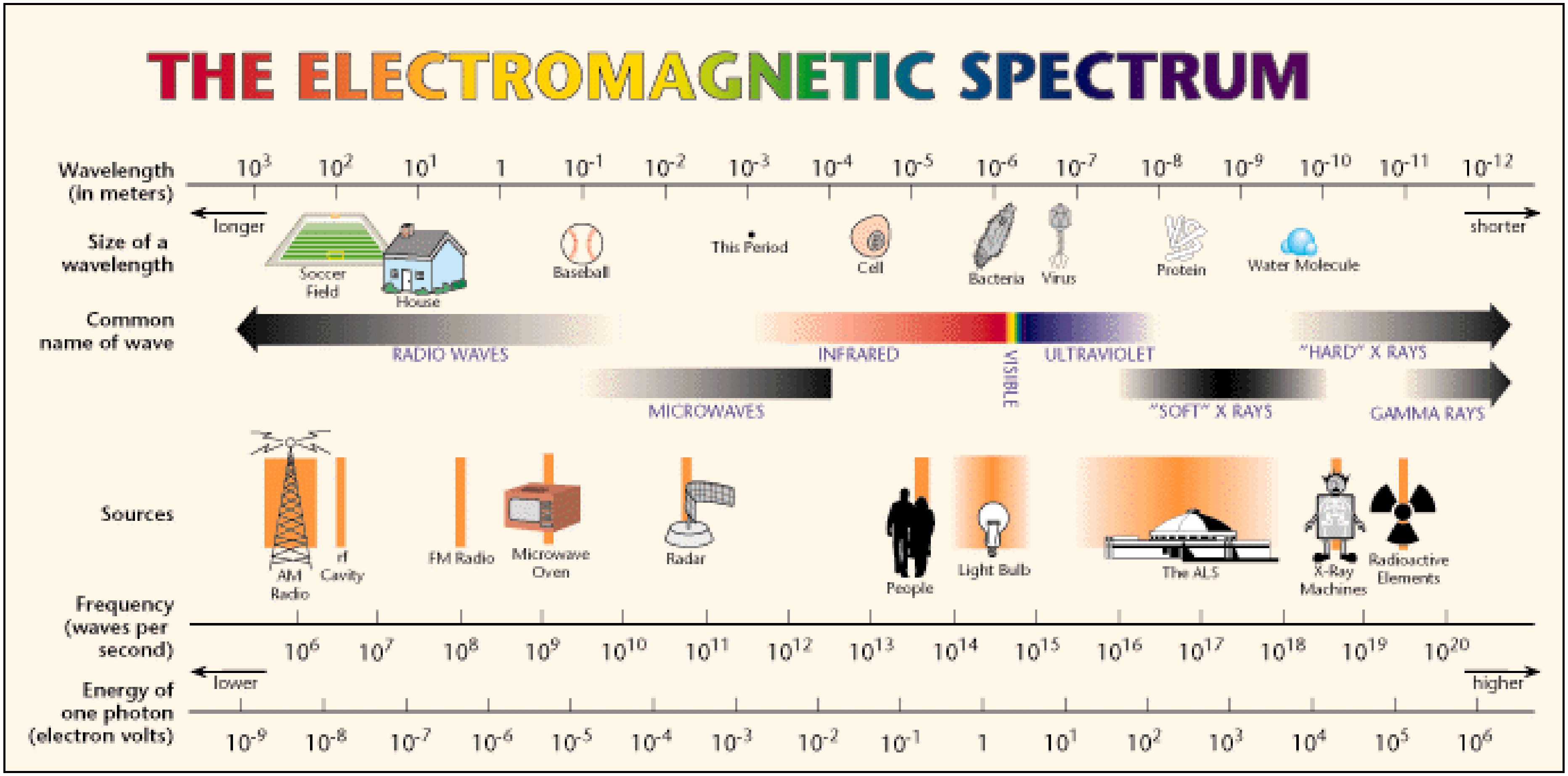
These RBC are ~7.5 thousandths of a mm across (0.0075mm)

Resolution

You can see finer detail the smaller the probe that you use…shorter wavelengths (higher frequency), and higher energy…



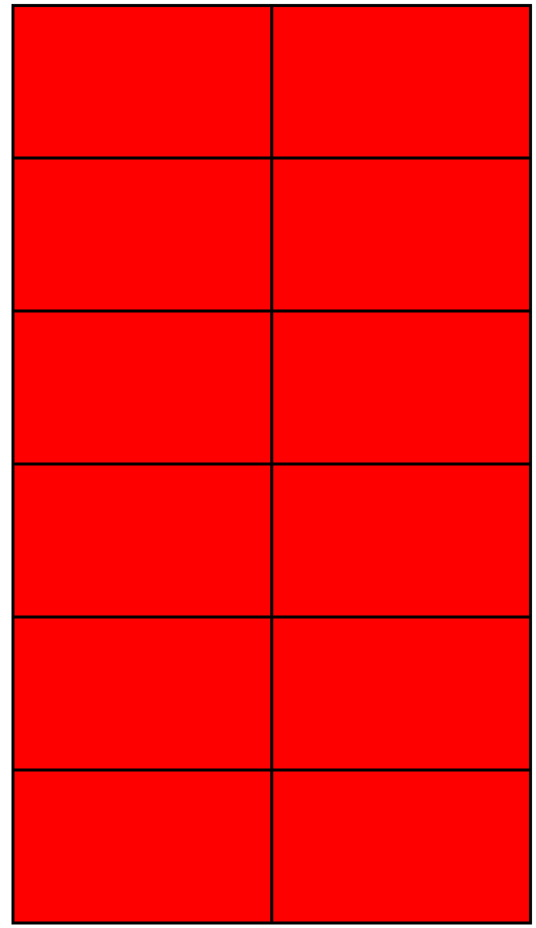
Resolution

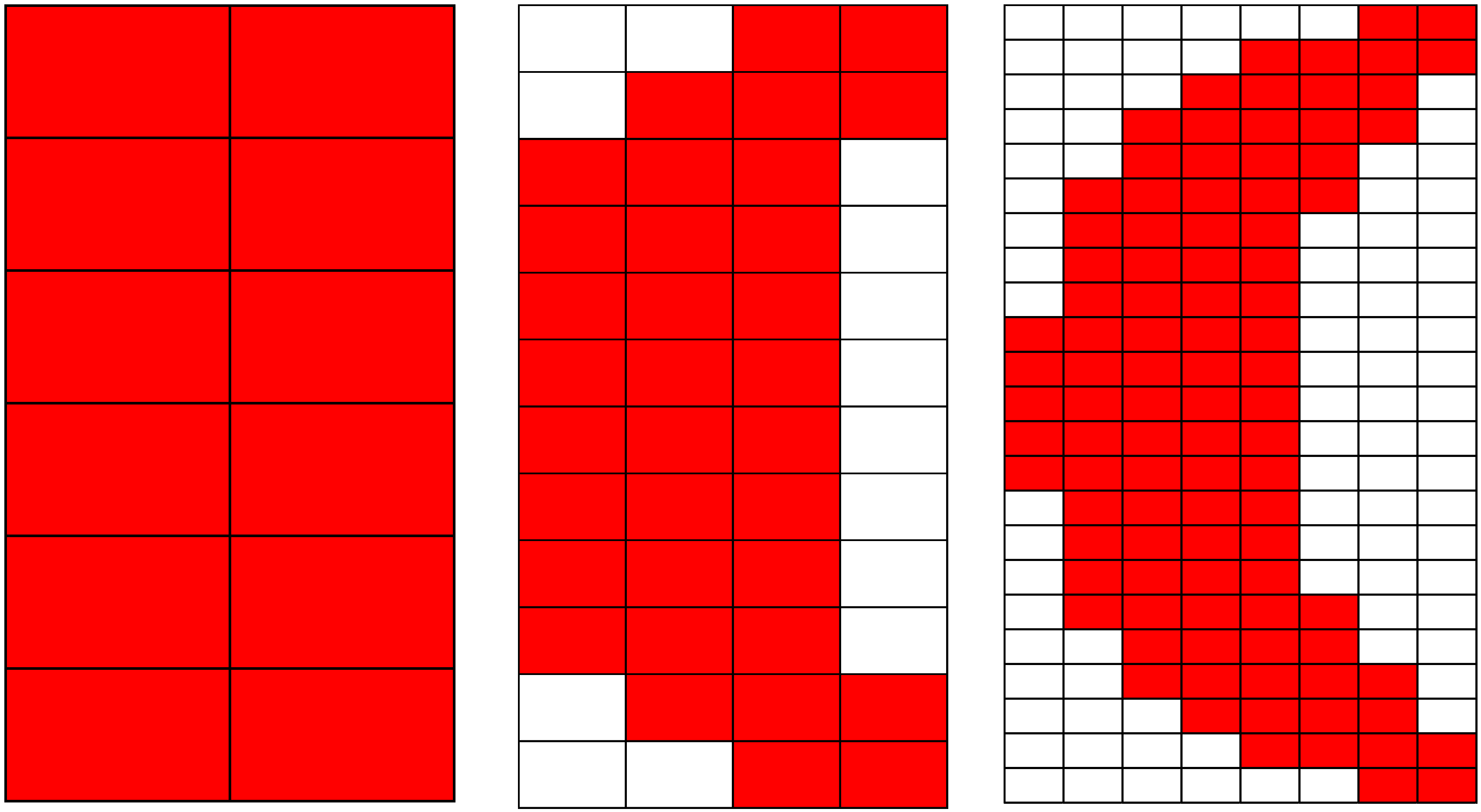


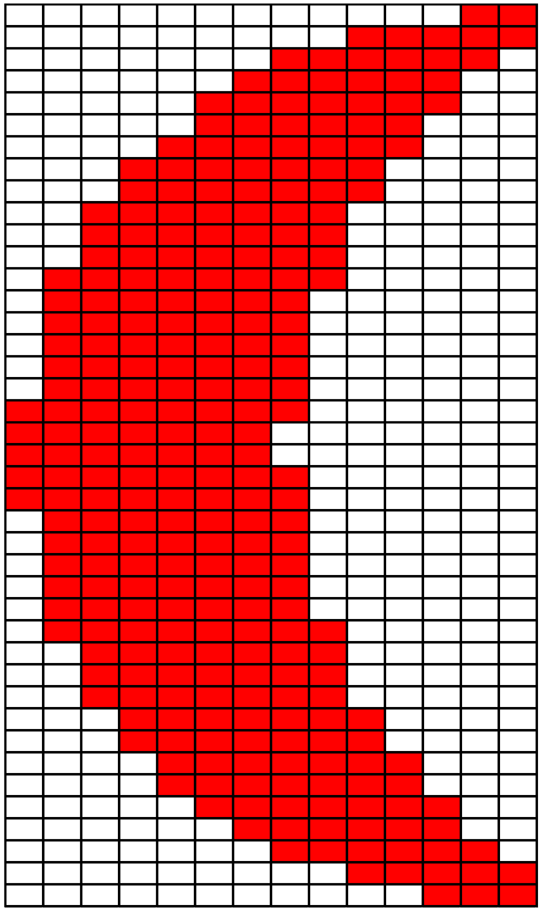
THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6

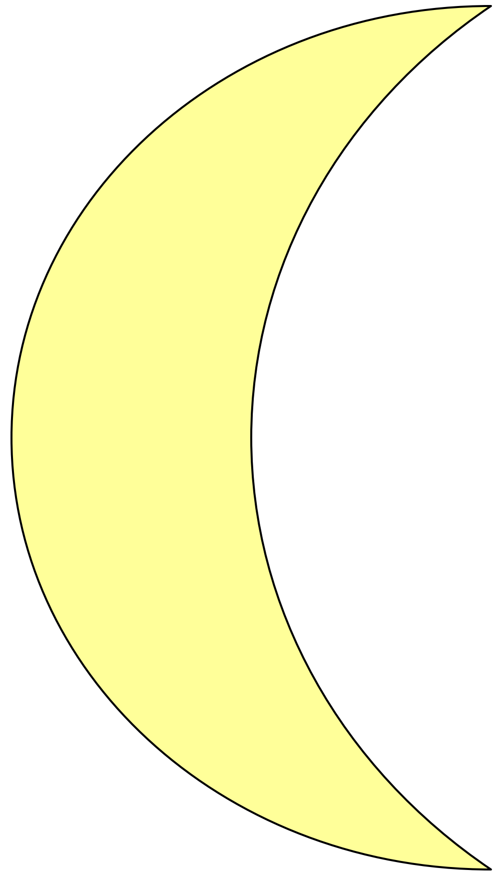
An example of Resolution

- So lets assume I have a grid (as shown), and something under the grid, and every place my object is in one portion of the grid, I get a 'hit'.
- Better resolution is the same as making the grid smaller…





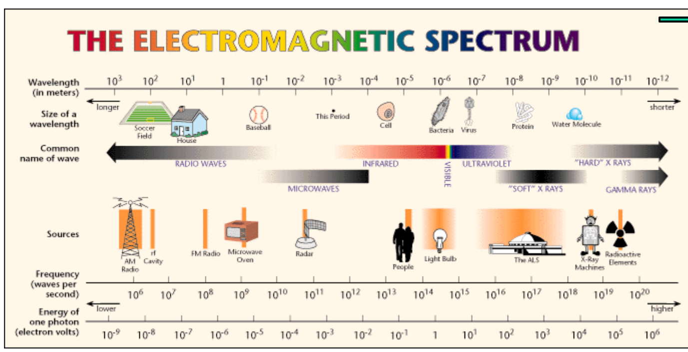




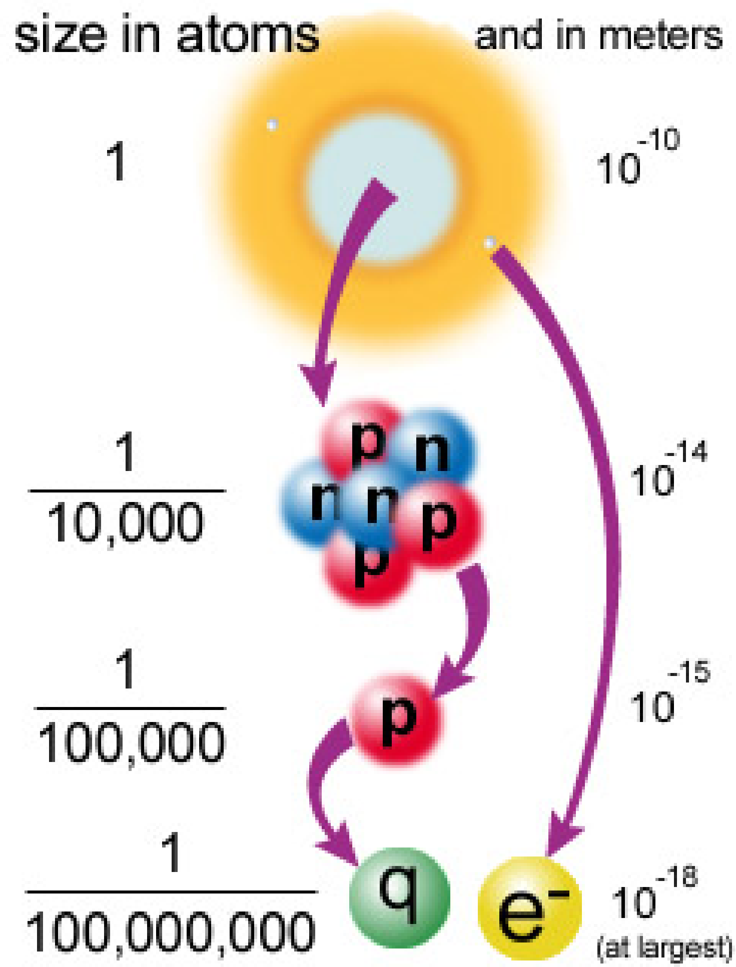
Better resolution lets us see things as they are…

…to Fermilab's scale…

So on the spectrum chart a few pages back, Fermilab explores stuff which is waaaayy to the right…



We want to explore about here on this scale!



Just for thought

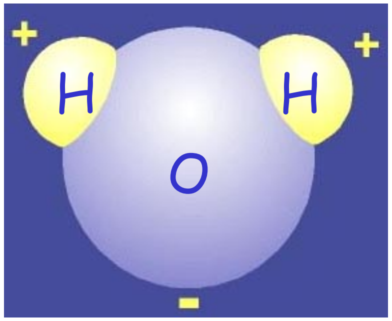
Some ideas…

- Along the edge of a normal ice cube, there are on the order of 100 million (100,000,000) water (H2O) molecules.
  - If you lined up that many kernels of popcorn, they would stretch 500km (310 miles)
- If you make a simplification, and just look at one of the hydrogen atoms in the water molecule, you'd find
  - A single electron, which is no more than 1/100,000,000 the size of the atom
  - A single proton, which is 1/100,000 the size of the atom
  - Nothing else.

Try that again

Short recap:

- There are ~100,000,000 water molecules along the edge of an ice cube.
  - Or, each water molecule takes up 1/100,000,000 of the edge.
- The hydrogen atom in the water molecule has
  - A single electron and a single proton which together have diameters 1/100,000 + 1/100,000,000 of the size of the atom or
    - 0.00001001 of the diameter of the whole atom
  - The rest of the volume of a hydrogen atom, 0.999999999999999 of it, is nothing.



This is true of all atoms.

This is what we, and everything else, are made of: at least 99.9999999999999% nothing.

Go figure.

The mission of the lab

Fermilab is a place in the world where people come to try and figure out, experimentally, just why the pieces of atoms are what they are. What are the fundamental pieces of matter? How do they interact? Why?

High Energy Physics does not look for applications of that knowledge. It strives to verify (or not) theories on how particles in nature interact with each other. This has implications on everything ranging from our understanding of the universe, to hand held GPS systems, to computers.

Off shoots of things that have been developed as a function of our mission include MRI technology, some cancer treatments, the Web (from HEP work at CERN), financial derivatives, data mining, and recently the means to revive old records.

Our most common 'product' are highly trained people…only a few actually stay in Physics.

Particle Physics 101

The current theory of the makeup of the universe is called "The Standard Model". In the model there are:

- 6 quarks
- 6 leptons
- Force carrier particles

The standard model does not explain everything. They haven't tied gravity in yet, for example.

It's a theory, some of which has been experimentally verified. It's the best thing we have going, so it's where we start.

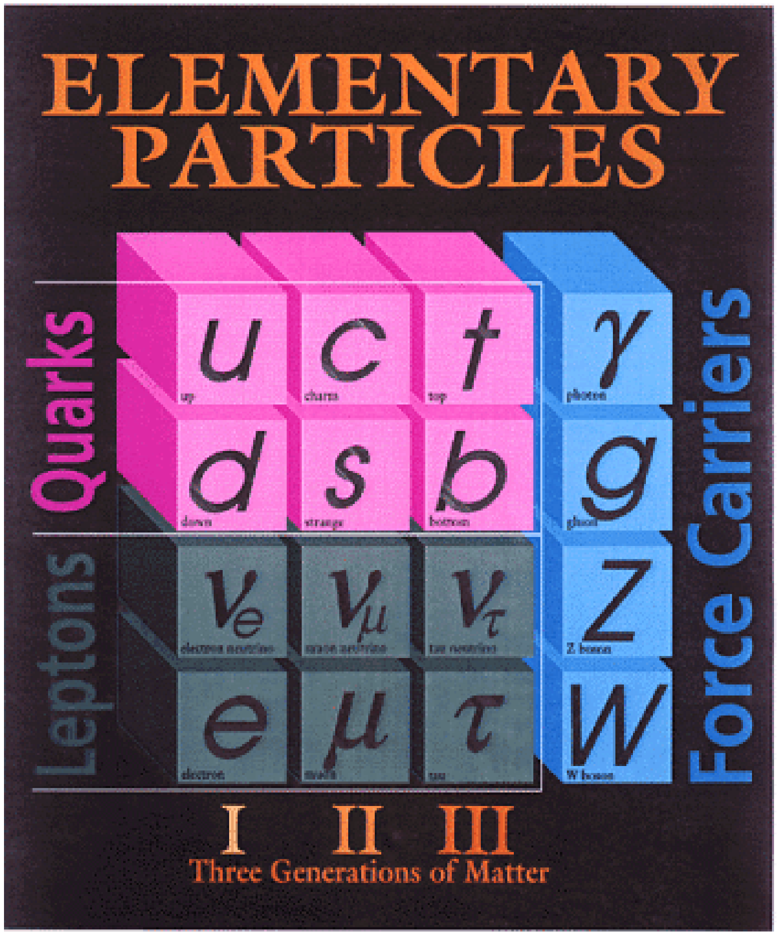
The Standard Model

Quarks and Leptons are the building blocks.

Up and down quarks make up protons (2u, 1d) and neutrons (1u, 2d). These make up the nuclei of atoms.

The electron is the most commonly recognized lepton.

Force carriers take care of the interactions between particles.



What's matter?

We'll start with matter…each quark or lepton can be classified with 5 properties…mass, charge, flavor, spin, and color.

Mass is…mass. Typically we think of this as 'rest mass'.

Charge…electric charge. Quarks have this in multiples of 1/3, leptons in multiples of 1.

These two are terms we're familiar with in life. For instance, an electron has a rest mass 9.28×10^{-31} kg (or 0.00000000000000000000000000000204 lb)

and a charge of 1eV

(or 0.0000000000000000001602 Amp-seconds (C))

The 'Normal' Stuff

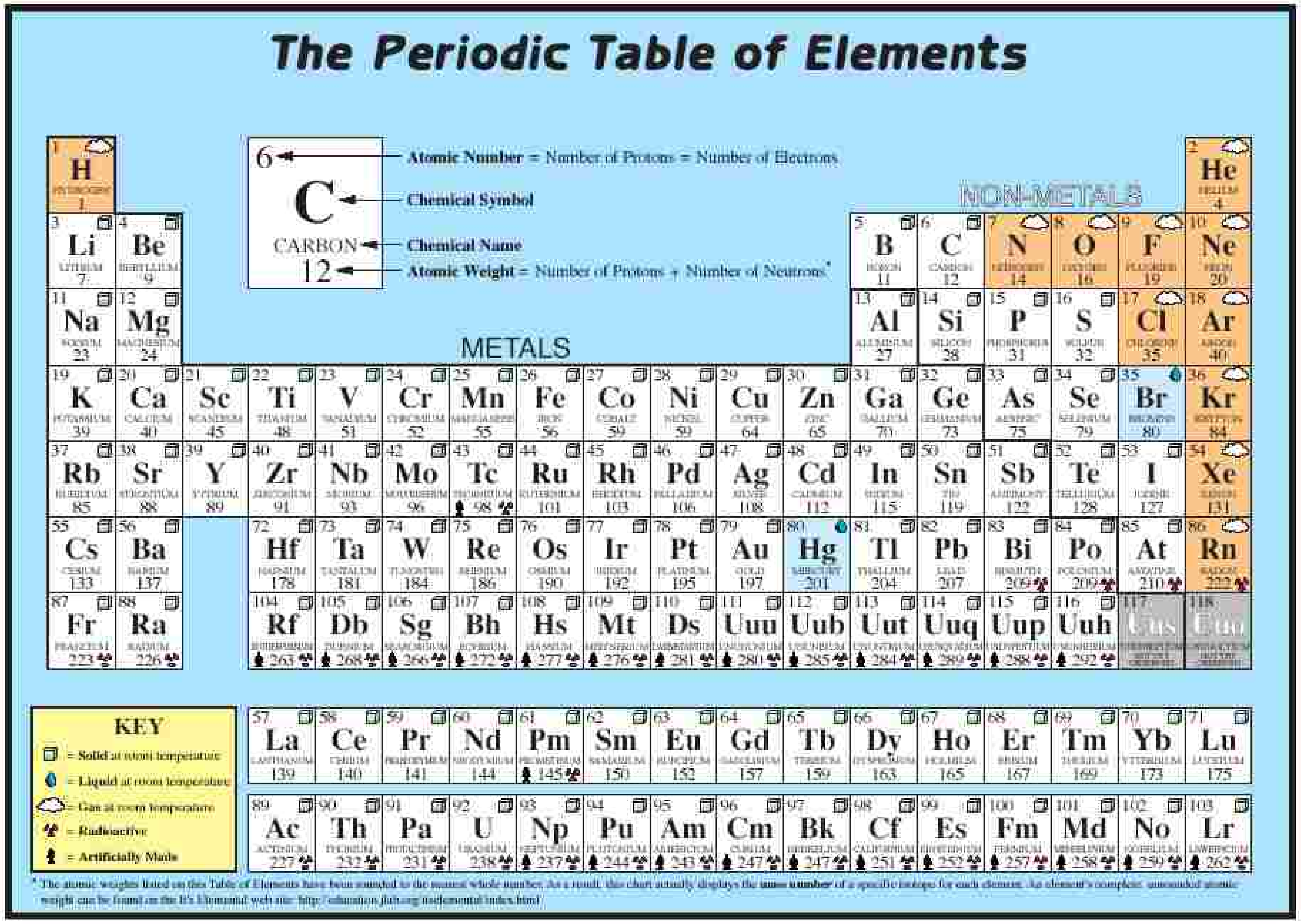
A summary table of particles we are 'familiar' with might look like…

	Mass (amu)	Charge (eV)
Proton	1.00728	+1
Neutron	1.00866	0
Electron	0.00055	-1

1 amu = 1.6604×10^{-27} kg

and from this, if you want to go into Chemistry, you're off to the races…

A Chemistry Moment…



Chemistry is another talk…

Back to Physics. While an electron is made of an electron (a fundamental particle, as far as we know), protons and neutrons are not fundamental.

- A proton is 2 'up' quarks, and a 1 'down' quark.
- A neutron is 1 'up' quark, and 2 'down' quarks.

An up quark has a charge of +2/3, a down quark –1/3.

- A proton, $2/3 + 2/3 - 1/3 = +1$.
- A neutron, $2/3 - 1/3 - 1/3 = 0$.

And the mass difference is explained by the small difference in the up and down quark masses.

By why does a nucleus stay together? Why does a proton stay together?

Color

Color, flavor, and spin are the 3 other properties we don't normally relate to in normal life

- the names don't mean anything→ they just had to be called something.

Color is relates to why a nucleus stays together, and we have a daily result of it. Color is something which interacts only over a short distance, but results in a very strong binding interaction.

At short distances, it's stronger than the electro-magnetic interaction, so protons (all positive charge) can stay together in a nucleus. Neutrons help!

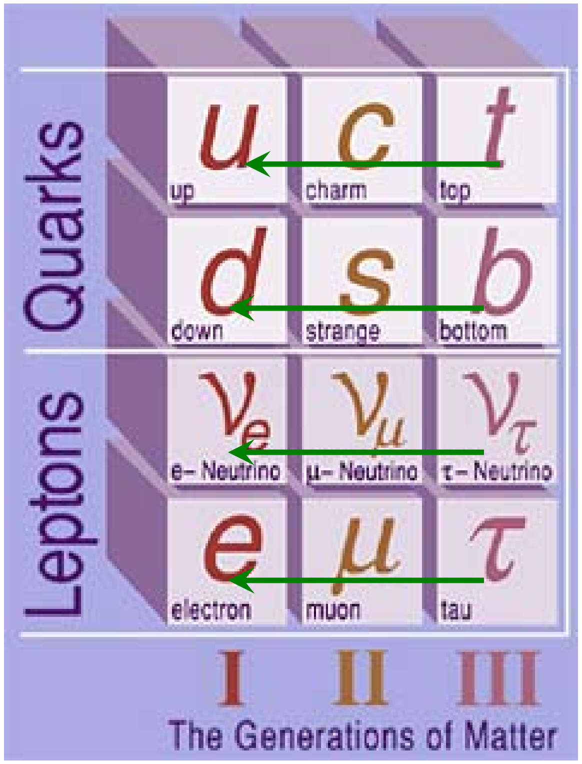
If you can break a nucleus apart, you get 2 smaller nuclei the mass of which sums up to a little less than the original

The rest goes into kinetic energy—mass is (becomes) energy—also known as an atomic reaction…

Families…

Flavor has to do with the 'generations' of matter. We typically see only the 1st generation, but the 2nd and 3rd generations can be seen or created.

The 2nd and 3rd generations will tend to decay back into the 1st generation in the family. Flavor is always conserved in this process…families stay together.



And finally, Spin.

Spin is not 'spinning'. It's a name applied to the intrinsic angular momentum and magnetic moments that particles appear to have.

Again, depending on their spin, particles appear to follow some laws, or not.

Fermions, which have spins in odd-half integers (1/2, 3/2, …) follow the Pauli Exclusion Principle.

- Leptons, quarks, and most composite particles like protons and neutrons are Fermions.

Bosons have integer spins.

- Force carrier particles, and some composite particles ('mesons'), are bosons.

Anti-matter

For each type of matter particle, there is also an 'anti-matter' equivalent.

It is identical to it's matter particle, BUT has exactly the opposite charge.

- Anti-quarks are designated with a bar on top…$\bar{u}$ or "u-bar"
- The anti-electron is called a positron…and designated e^+
- The opposite of a proton…an antiproton.

When matter and anti-matter meet, they annihilate each other and release pure energy. (we can do things with this…)

And if they are equal and opposite, why is there so much more 'matter' than anti-matter in the universe?

- We don't know…(but there are 2 experiments, one in Japan and one in California, working on it…)

Interactions

Particle interactions are classified in 4 ways…

- Electromagnetic
- Strong
- Weak
- Gravity

Electromagnetic interactions are due to the residual electric charge of one atom acting with another. It is responsible for most of the 'everyday' things we see…friction, magnetism, surface tension, things being 'solid'…

Electromagnetic interactions are transmitted by photons. Light is a portion of the Electromagnetic spectrum, which is made up of photons of different wavelengths.

Interactions

Strong interactions are what hold a nucleus together (the residual strong force is ‘strong enough’ to overcome the electromagnetic force which would want to blow a nucleus apart).

The strong force deals with color changes in a nucleus.

The force carrier for the strong force is called a ‘gluon’.

Interactions

The weak interactions are involved with the decay of one quark or lepton into another quark or lepton of the same family.

- Decay of a neutron into a proton and a electron neutrino (Beta decay) fuels the sun…

The property this is associated with is flavor.

The weak interaction has been determined to be related to the electro-magnetic interaction, so many times now these are called together 'Electro-Weak'.

- The unification of these two theories took years to figure out and prove…the unification of gravity and the strong interaction continue to be a major goal of the field

Interactions

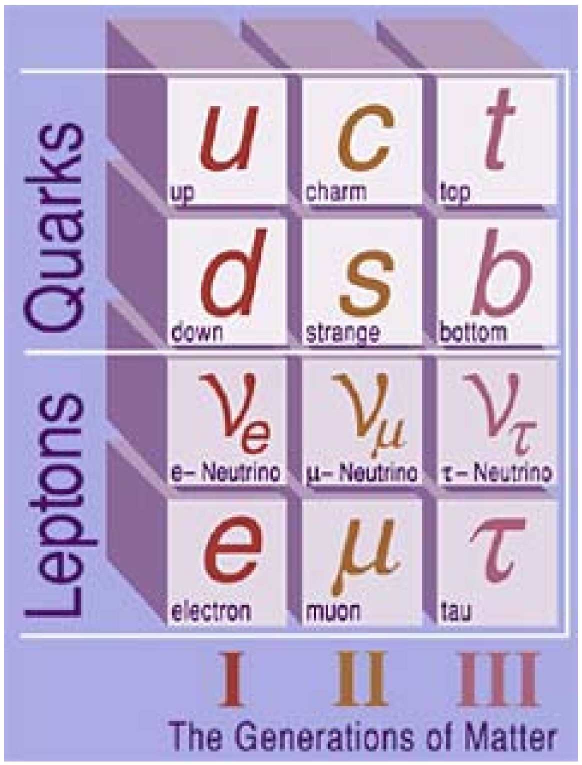
Gravity is the attraction of 2 masses to each other. It is much weaker than the other interactions, but works over much greater distances.

The property gravity is associated with is mass.

No one understands how mass 'is', and how gravity fits into the model.

A force carrier called a 'graviton' is hypothesized.

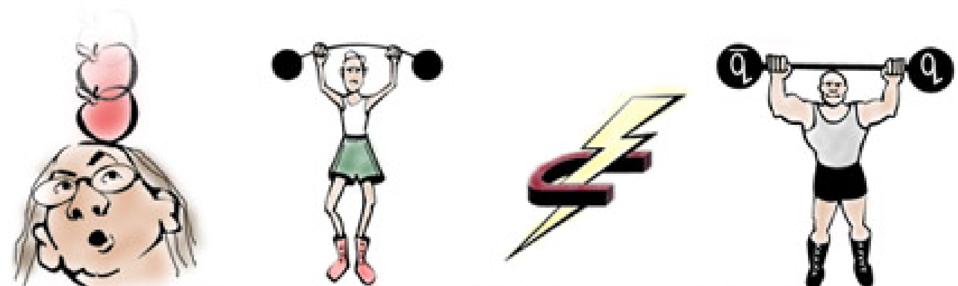
The summary



There are:

- 12 quarks and leptons (and their anti-particles).
- 5 properties of each
- 4 interactions

Got it? Good!



	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Is this Empirical or Theoretical?

Both.

If it seems we have some hodge-podge of 'particles', with some assigned 'properties', with some 'interactions', some of which we can touch, you're right.

- But a small number of 'elementary particles' can build the entire universe.

Independent of the names of the various bits, it forms the most consistent set of rules for how everything fits together that we have. There isn't anything better.

But this is by no means complete, and the empirical nature of some of it is a real bug to a lot of people.

So we continue to work on it…how? By refining, breaking, and redefining it.

The tools--Particle Accelerators

A particle accelerator is the 'microscope' side.

There are 2 ways to generate information…

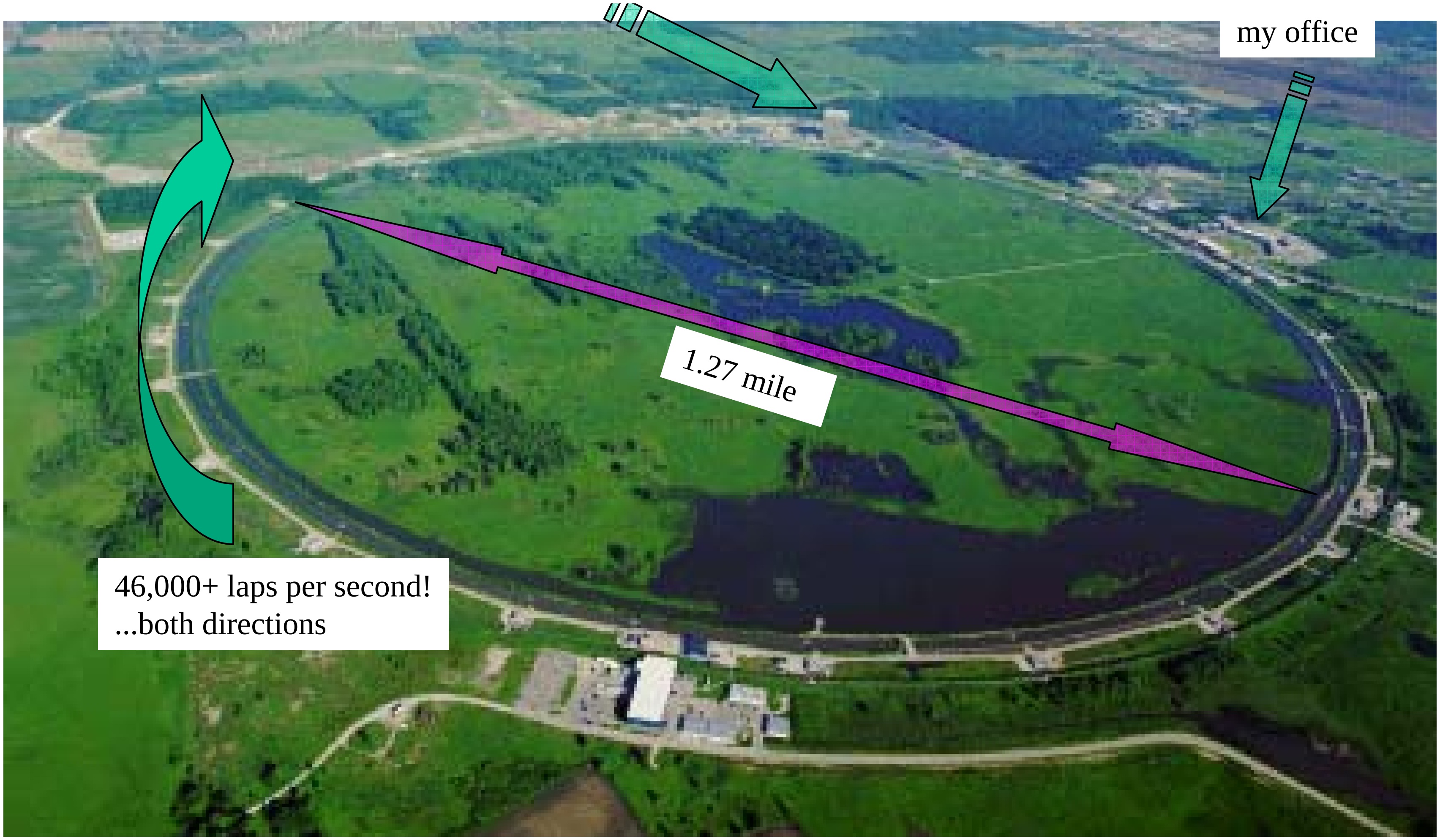
- some accelerators shoot beams at a 'target' (this would be what was on the slide under a microscope)
  - This is called a 'fixed target' experiment
- Others shoot beams at each other, and look at the collisions resulting from that
  - This is called a 'collider', or 'colliding beam' experiment.

Fermilab does both.

(ps…sometimes, physicists are clever and cute in naming things "quarks" for instance…other times it's just straightforward…when in doubt, guess the obvious…you'll have a 50/50 shot at getting it right)

Fermilab

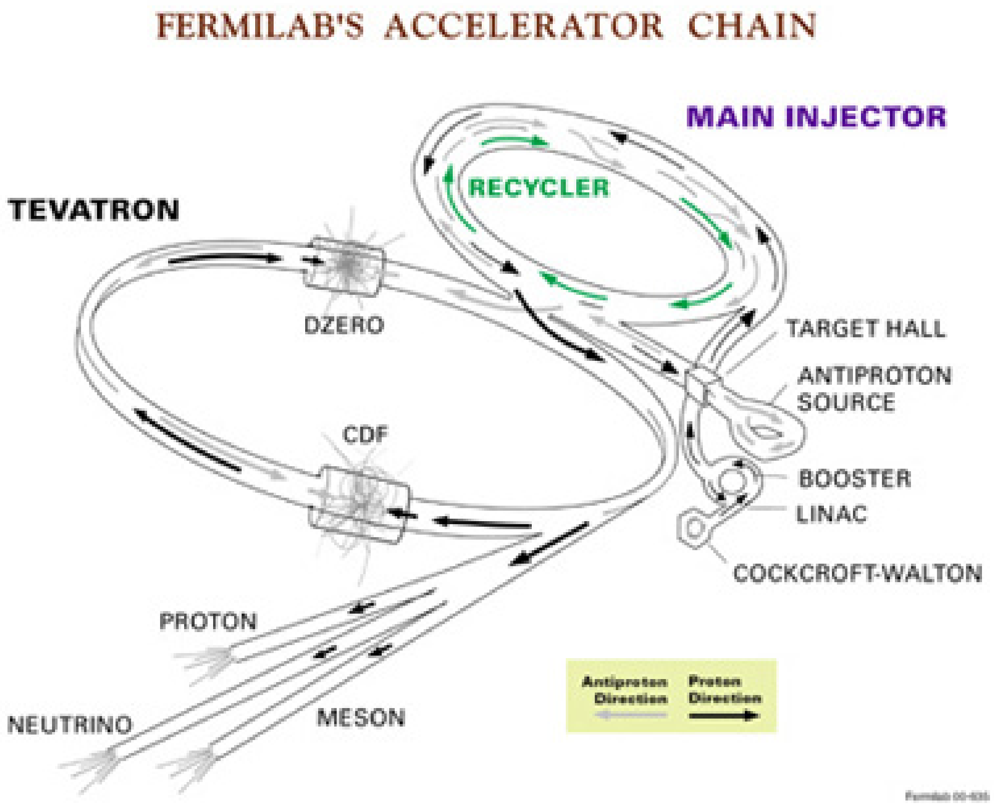
16 story building (you are here)



Accelerator Chains

Fermilab is actually a chain of accelerators.

Like a bike or a car, it's more efficient to use steps in acceleration ('gears') rather than a single machine.



How do you accelerate a proton?

The proton needs to go across a potential energy difference.

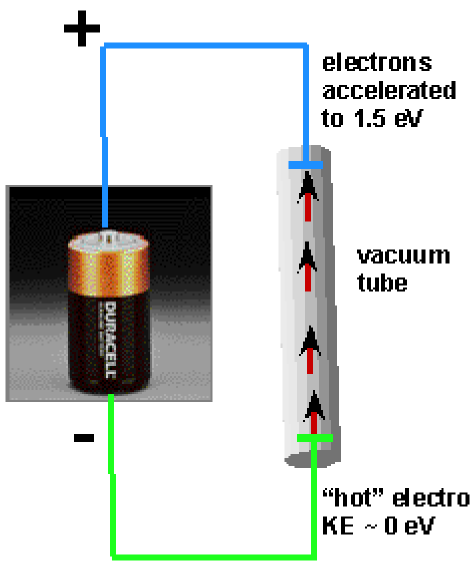
A simple example of this is…a battery.

- The voltage on a battery is a potential (potential energy).
- A charge moving across that potential gains energy.
- An electron volt is the amount of energy gained by 1 electron moving across a potential of 1 Volt.

So…an accelerator is theoretically possible by using a string of batteries.

- Use a 3V battery…we want to get to 1,000,000,000,000V, so we need 333,000,000,000 batteries.
- Lithium cells are 3mm thick, so our battery accelerator would be 1,000,000 km long, and at ~$1 each (low!) cost 333 Billion dollars!

Fermilab was built for factors of hundreds less.



Starting Out

The 1st step in the chain is the Cockroft-Walton (pre)accelerator.

This device ionizes hydrogen (H^-), and accelerates them by a positive voltage to 750,000 eV (750keV).

A normal television operates at about 25 keV.

The Linac is about 500 feet long. It uses oscillating electric fields to accelerate the H^- to 400,000,000eV (400MeV).

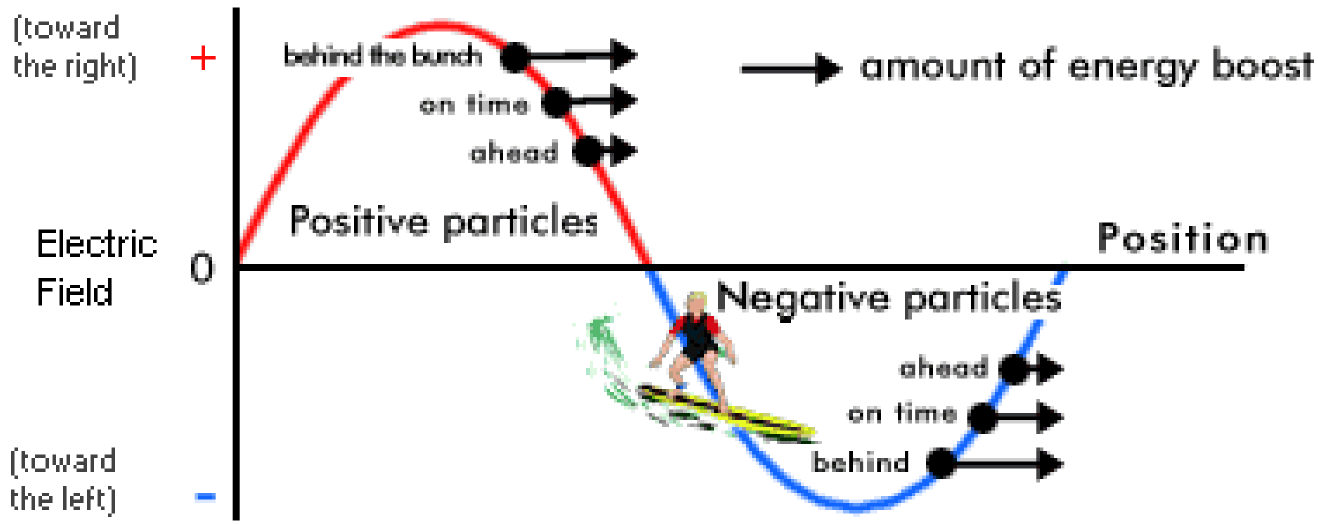
At the end of the Linac, the Hydrogen passes through a carbon foil, which removes the electrons and leaves only the Hydrogen nucleus…a proton.

RF Acceleration

Already we're making choices.

The linac, and everything downstream, uses oscillating electric fields.

- **This is done for a practical reason…it's much easier to make these sorts of fields.**
- **But there is a timing problem…you must have the particle catch the right portion of the wave…otherwise it slows down!**



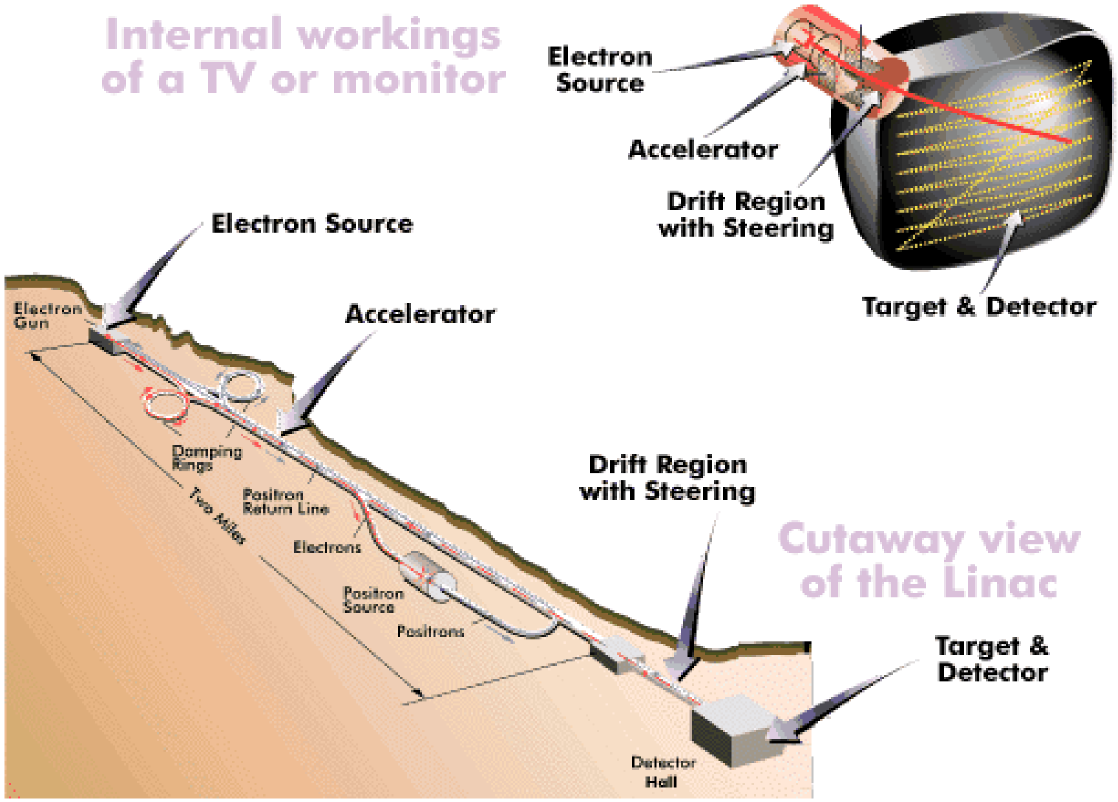
Linear Accelerators

Next choice…straight or circular?

A 'straight' machine is called a Linac

- It's "linear"
- It's a whole bunch of RF cavities in a row.
- It's better, as you are accelerating electrons or positrons
- You need a long, narrow piece of land

SLAC is the largest in operation



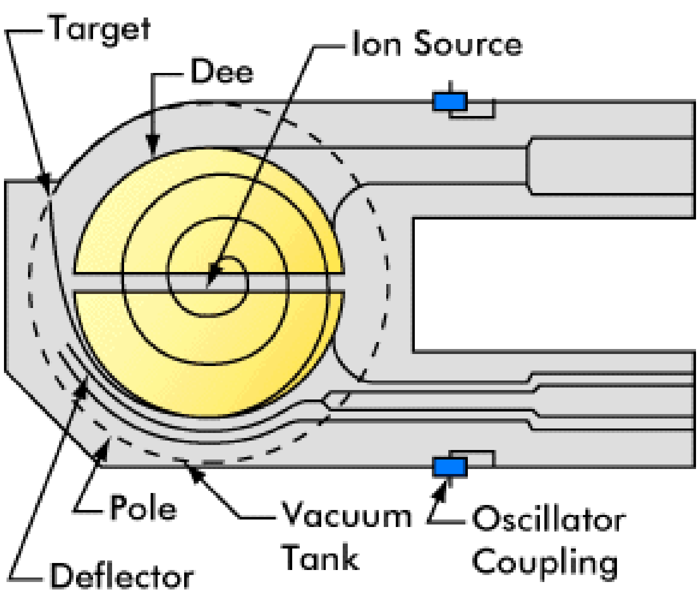
Synchrotrons

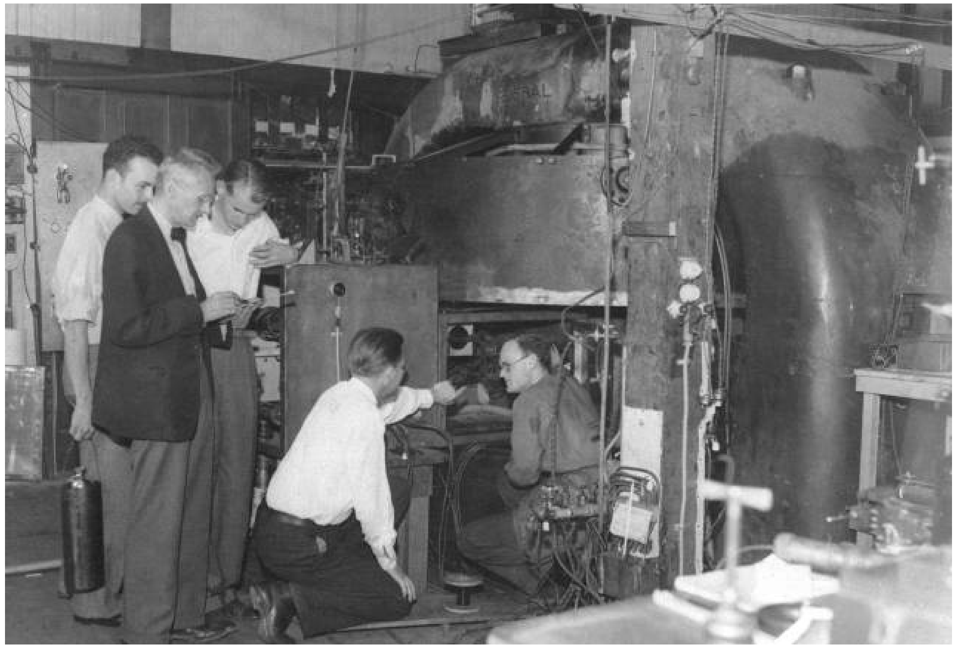
In other cases you find it more sensible to have a single acceleration section, but steer the particle through that section multiple times.

- It can be more efficient
- You can 'store' particles in the loop for some hours
- The RF section is shorter
- MOST of the ring are magnets, to keep the beam in a circle, and return them to the RF section again
- You must be able to vary either the magnetic field (or the radius), 'synchronized' to the energy

Synchrotrons (Cyclotron, actually)

The first circular accelerator was conceived by E. O. Lawrence in 1929, and developed at the University of California in the 1930s.





The Booster & Main Injector

The Booster takes the protons up to 8,000,000,000 eV (8GeV)

The protons makes 20,000 laps of the machine during this time.

The Main Injector accelerates particles to 150GeV. It also:

- Makes 120GeV protons for pbar production
- Accelerates pbars to 150GeV

These are both 'conventional' machines

The Tevatron

The last step is the Tevatron. It accelerates protons and antiprotons to 980 GeV, and brings them to collision at B0 and D0.

- The protons and anti-protons are going ~185,800 mps
  - 185,800 mps = 669,600,000 miles per hour
- The speed of light (c) is 186,000 mps
  - $V_{p,\ pbar}$ = 0.9989c

The Tevatron was built in the early 1980's as an upgrade to Fermilab, which had been operating for the previous ~15 years with conventional magnets, at lower energy.

Making higher field, superconducting magnets, was the cheapest way to accomplish the upgrade.

The Tevatron

As an upgrade, the Tevatron needed to fit in existing space, in the existing tunnel…a tight fit…

The Tevatron, the highest energy machine, is the small machine crammed in the middle in this picture

On the beam

The trick with the Tevatron, and any HEP accelerator, is not necessarily the total amount of energy in the machine.

The real trick is the energy density. There is an awful lot of energy packed into a very small volume.

The current in the Tevatron can be calculated by the number of particles, their charge, and the revolutions…

- 240E9 x (1.15) x 36 x 1.6E-19 Coulombs/proton x 47.7E3 revolutions/sec = 76 mA. (not much, in your house)

Doesn't sound like much, but total stored energy is:

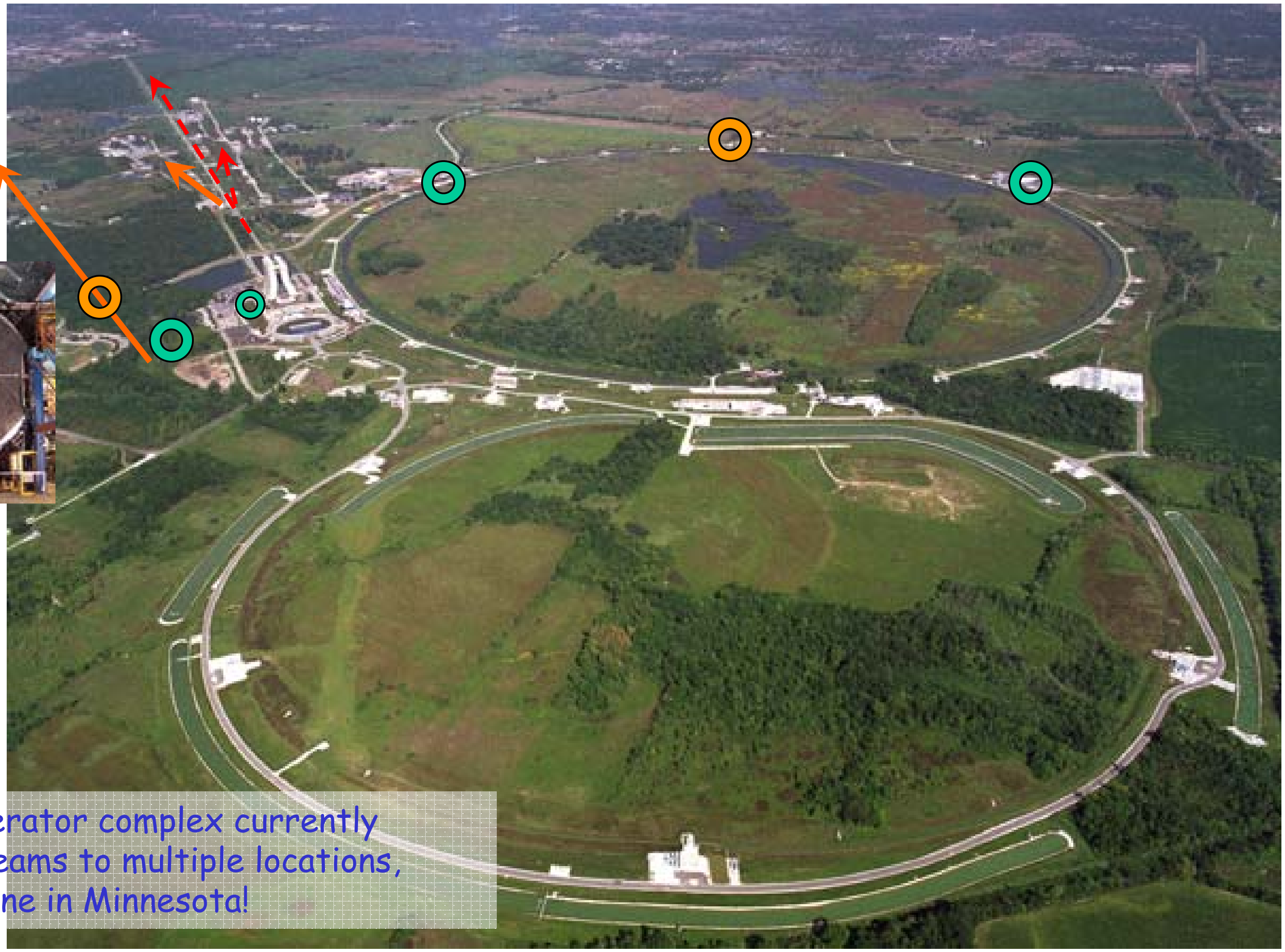
- 240E9 x (1.15) x 36 x 1.6E-19 Joules/eV x 980 GeV = <u>1.6 MJoules</u>.

For comparison, total stored energy in a 2 ton automobile travelling at 60mph is

- 1/2 x 4000 lb x .45 kg/lb x (60mph x 1609 meters/mile x .000278 hour/sec)**2 = <u>0.65 MJoules</u>.

The current accelerator complex

Soudan, Minnesota



The accelerator complex currently delivers beams to multiple locations, including one in Minnesota!

The Homestretch!

So we've completed the microscope, now for the 'eye', or the detector…

Fundamentally, detectors have two parts…tracking and calorimetry. There is a 3rd, particle ID, which I won't talk about much.

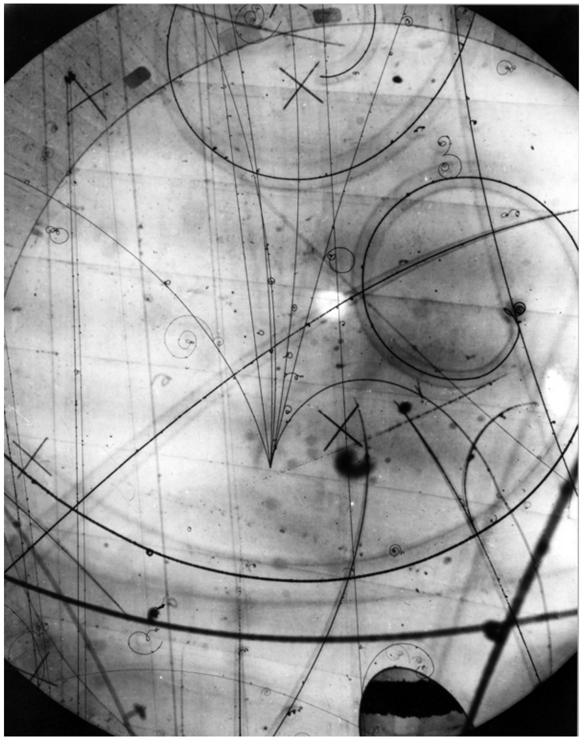
Tracking is just that…determining a track, or a path, for each particle.

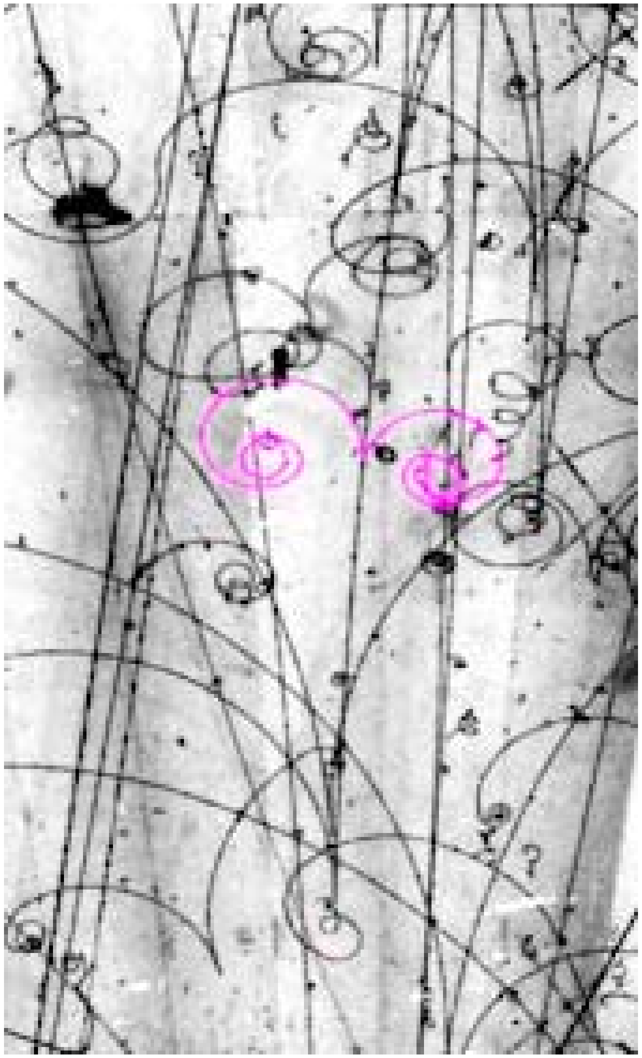
Calorimetry is quantifying the energy contained in each particle (think of 'calorie')

The trick is that the particles are very small, very quick, very energetic, and you get a new set of data to measure in less than a millionth of a second.

Detectors…

These are old Bubble Chamber photographs…you may be familiar with them…they were used for both tracking and energy

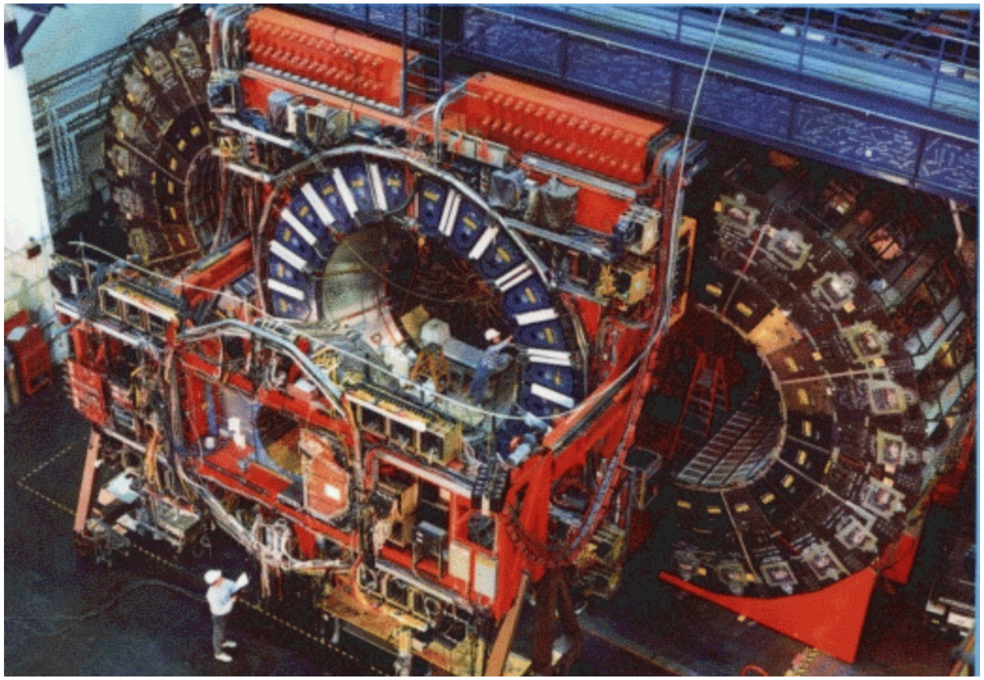




CDF

This an picture of 'CDF' in 1988, one of the places we'll visit later.

It's 3 stories tall, weighs 5000 tons, and measures particle tracks and energy…but, basically, has only a couple of parts

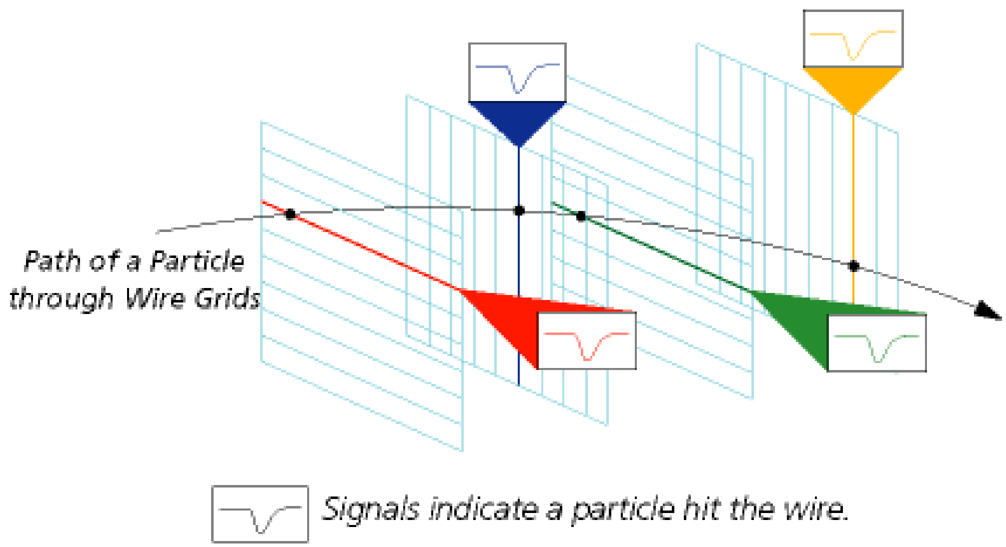


Tracking

Tracking records a path. This is done with electrical signals (wire or silicon strips), or light and scintillating fibers or tiles. The choice depends on resolution, space, and cost.

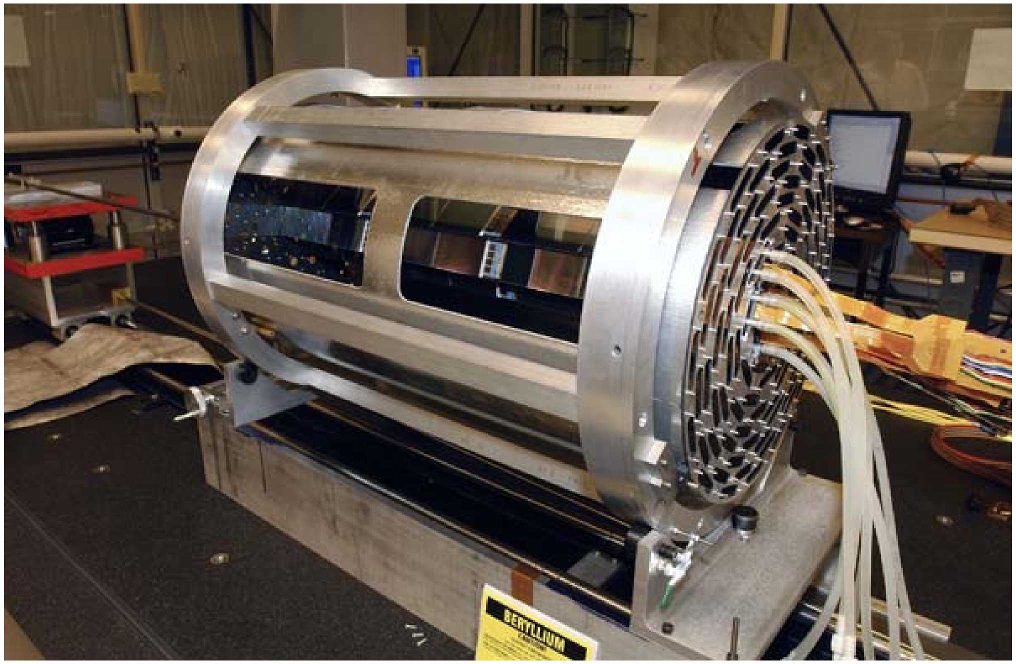
Wires might be at different angles with respect to one another to help determine the path.

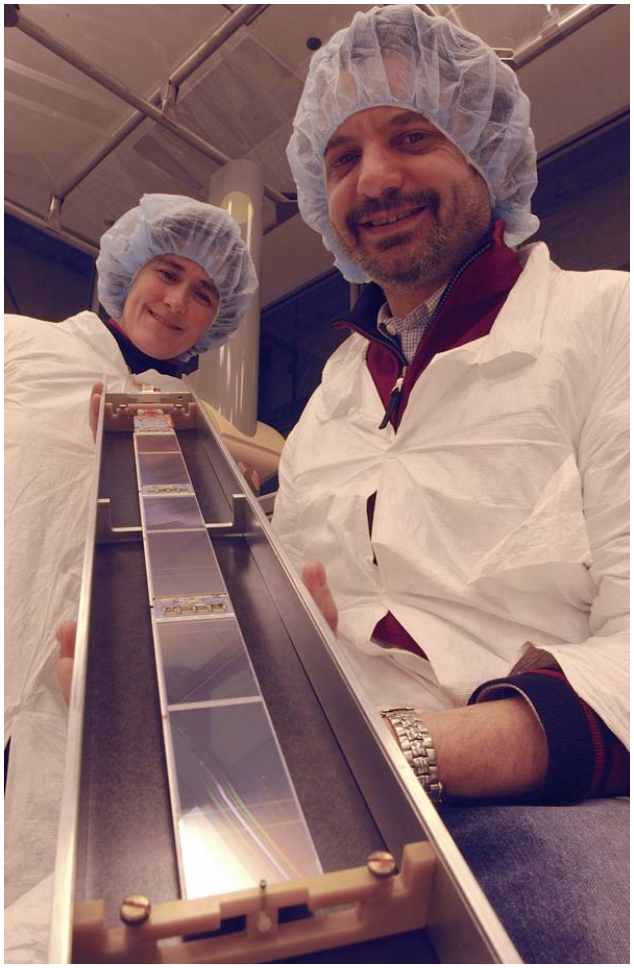
The whole assembly probably is in a magnetic field to help identify charged particles.



Tracking

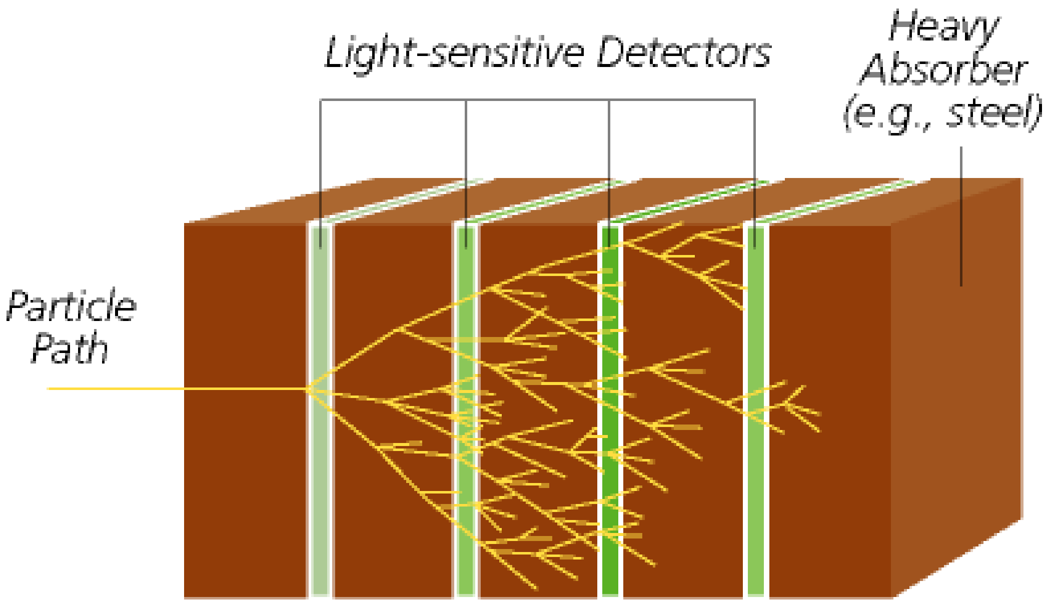
This is a silicon tracker from CDF. There are thousands of strips in one sub-assembly, which is two sided. They are assembled into an approximation of a cylinder, in many layers, very near the IP.





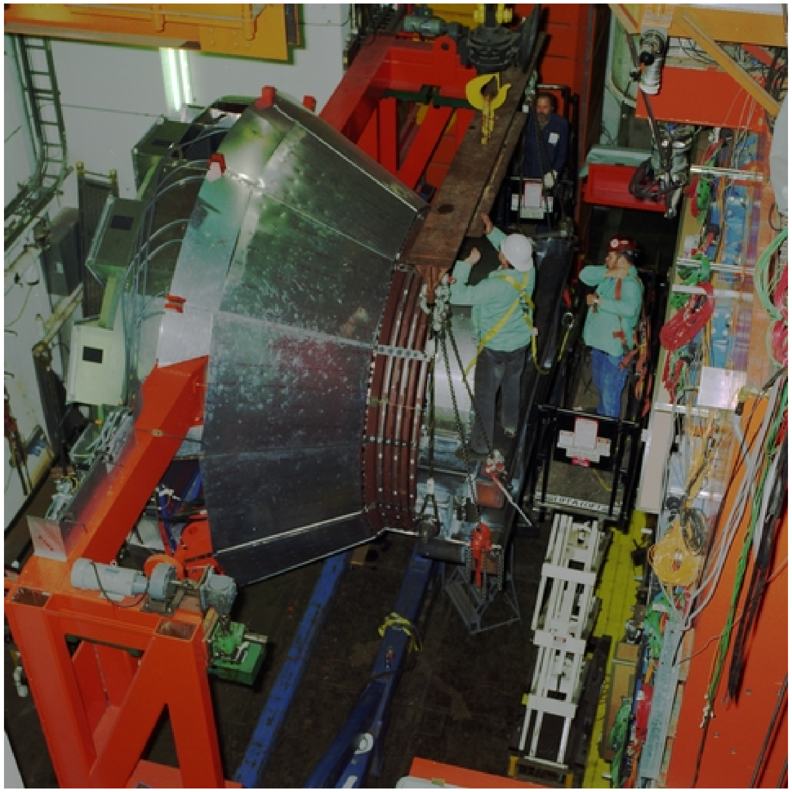
Calorimeters

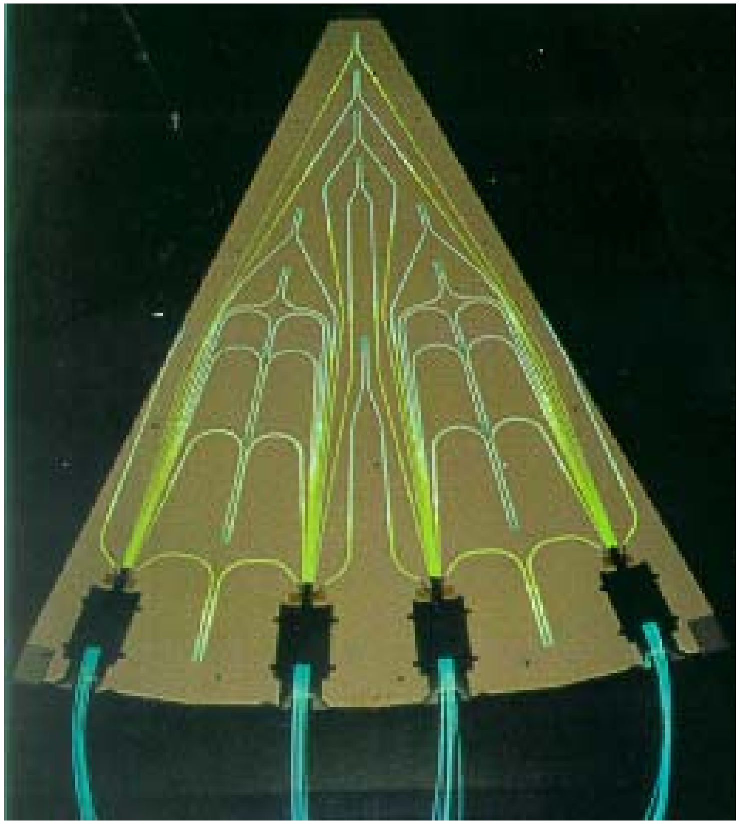
Calorimeters measure the amount of energy in each particle. The can be segmented to give some amount of directional information, but more coarsely than a tracker (cost goes up with more segmentation).



CDF Calorimetry

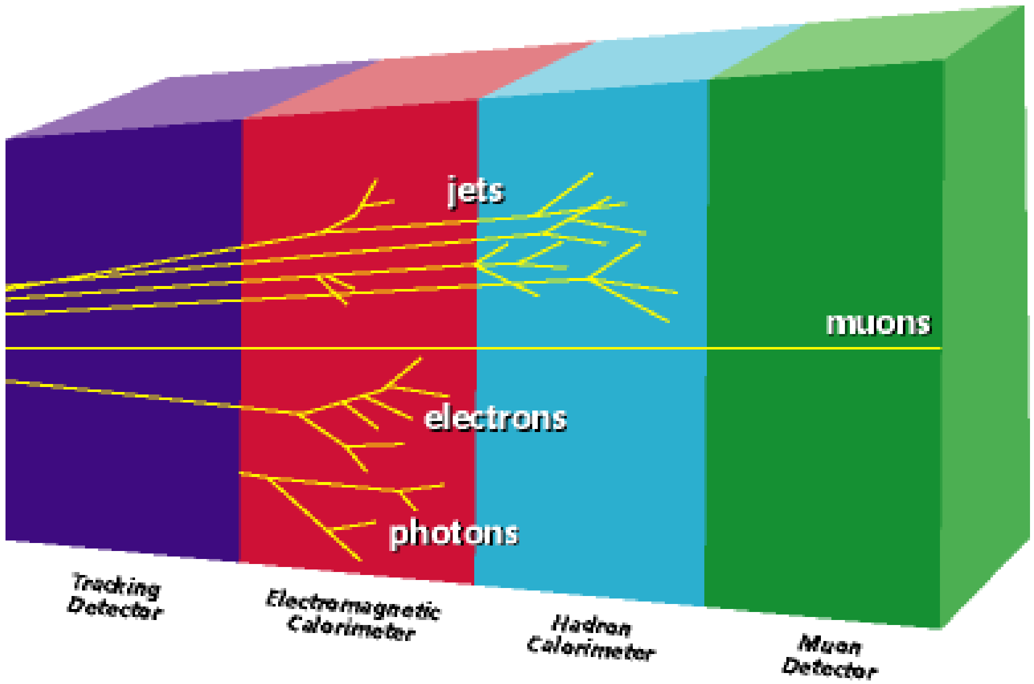
The CDF End Plug upgrade reworked the electromagnetic and hadron calorimeters, and the position detector ends of CDF. It's segmented into 30 degree sections, and each section had 'tiles' of scintillator, each read out by it's own light fiber.





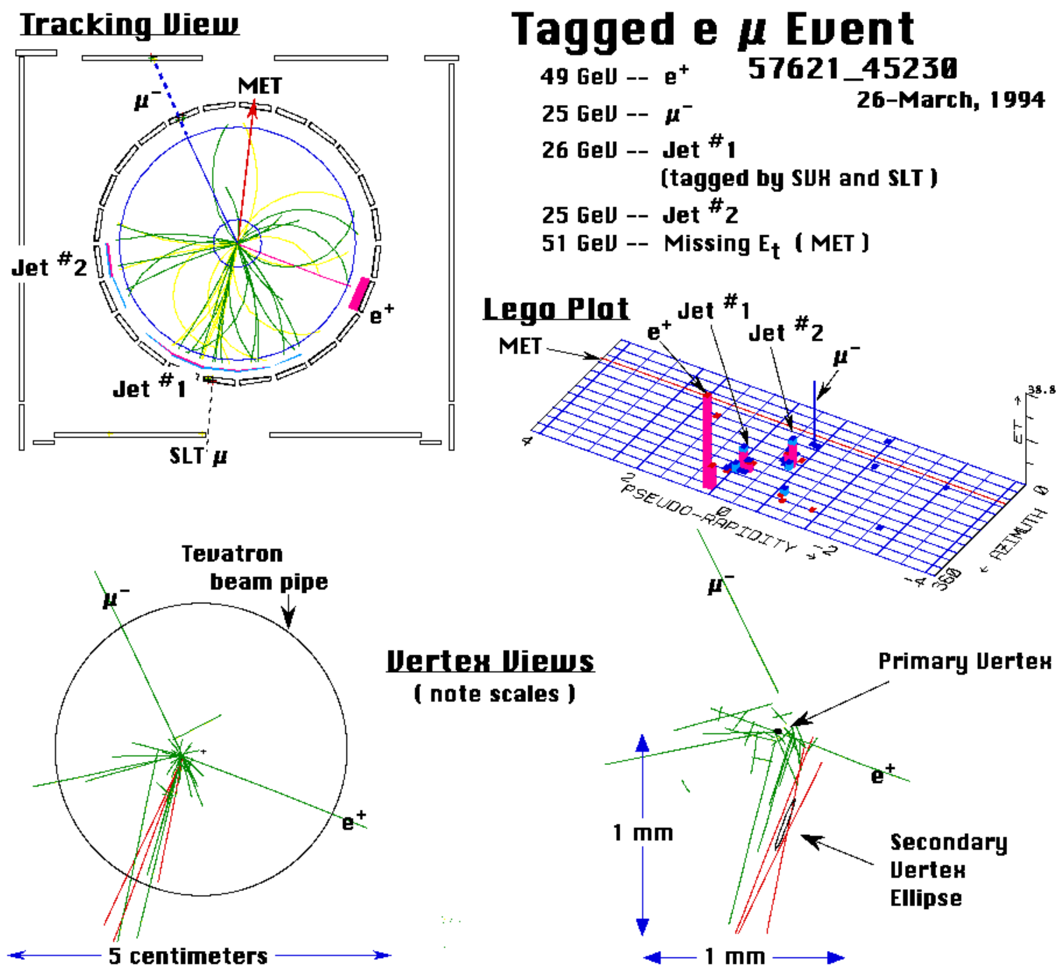
Putting it all togther

Since the characteristics of particles are different, you need different layers…the concept is the same, but they are engineered to be tuned for one particle or another…and a full detector ends up with many layers.



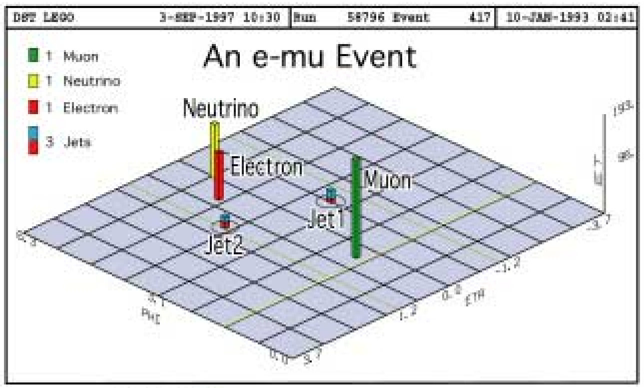
A 'top quark' event from CDF

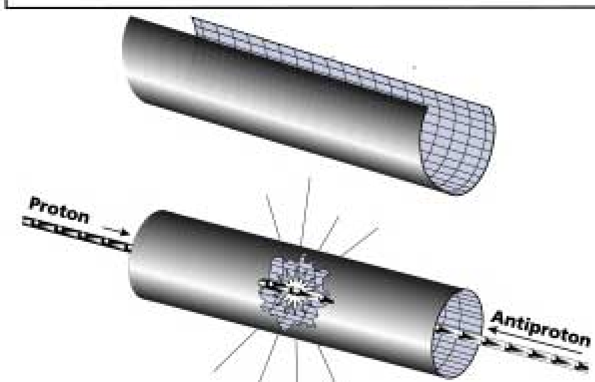
- This is a summary of a top quark event from CDF, which shows the tracking, vertex, and energy summary from a single interaction in 1994.
- A top quark event is very rare. CDF And D0 announced the discovery of the top quark after collecting around 100 top events, out of billions of proton-anti-proton collisions.



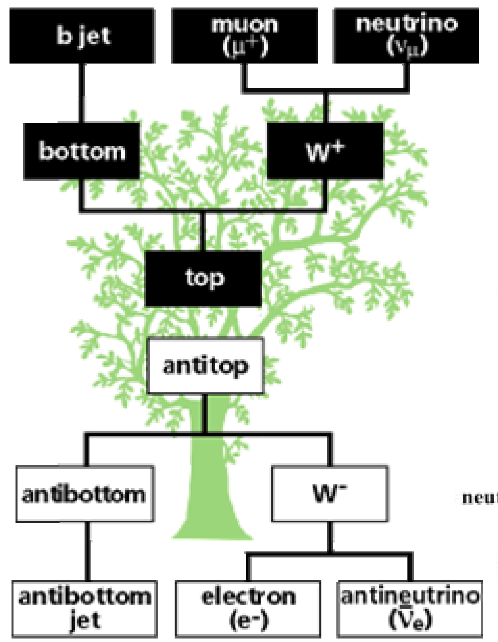
A Top Event

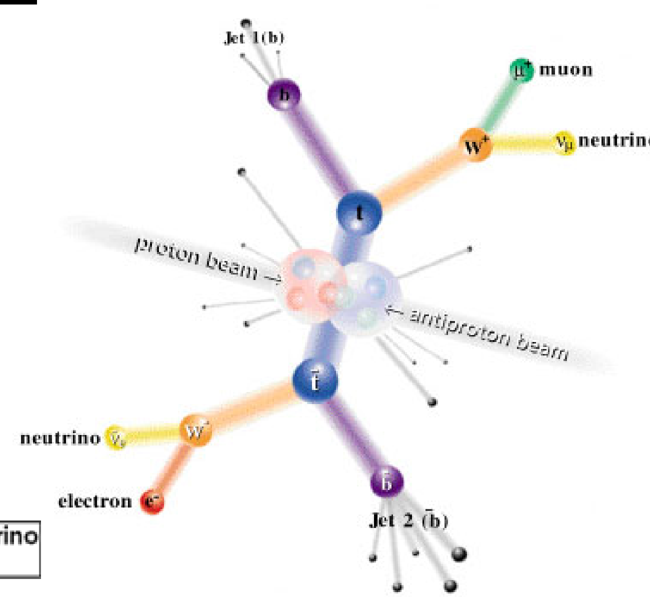
This is an artist's cleaned-up view of the same interaction. Every part of the CDF detector had to exist to gather the data, and piece it together in a manner that let them identify particles and determine what had happened.





Collision in Calorimeter





What next?

The Tevatron will be the premier high energy physics accelerator in the world for the next 5 years. After that, a larger machine being built in Switzerland will come on line.

The universe is it's own accelerator…there are unexplained, very high energy particles that come through the atmosphere all the time (Cosmic Rays). We have helped set up a detector in Argentina to understand these.

Fermilab is looking into building a new machine, which may focus on neutrinos or on electrons. The mass of neutrinos (thought to be zero until a few years ago), is a very big deal. We only know where about 5% of the mass of the universe is…this might explain another 20% or so.

Even though it's much cheaper than stringing batteries together, future larger machines will likely always be international. They are expensive, and not usually a funding priority (but they should be!).

What next?

You made it!

If you're dozing, it's a good time to wake up.

If you're already awake, we can do questions before going on the walk part…